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Energy Procedia 52 (2014) 142 – 149

Energy

Procedia

2013 International Conference on Alternative Energy in Developing Countries and
Emerging Economies

Four Zones Modeling of the Downdraft Biomass Gasification Process: Effects of moisture content and air to fuel ratio

C. Dejtrakulwong^{a*}, and S. Patumsawad^b

^a*The Joint of Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi, Bangkok,
(Thailand)*

^b*Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok,
Bangkok, (Thailand)*

Abstract

A mathematical model of a biomass downdraft gasification process has been developed. The model was considered to be four modules that are drying, pyrolysis, oxidation, and reduction which the products of upper module will be the reactants of the next. The one-dimensional kinetic finite rate models were applied to drying and reduction modules. The pyrolysis model took place when drying temperature reached 473 K. The equilibrium sequence model was used to describe the oxidation process by considering the sequence of order of reaction rates. For the model validation the comparison showed a good agreement. In the parametric study the moisture content increasing affected the height of drying, and pyrolysis zones increasing while the critical char bed length of reduction zone decreased from 0.53 to 0.25 m. The height of these zones decreased along A/F increasing. The results of this study can be used in the reactor design evaluation.

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Selection and peer-review under responsibility of the Organizing Committee of 2013 AEDCEE

Keywords: Gasification; Modeling; Biomass; Downdraft gasifier; Synthesis gas

1. Introduction

To solve both of the energy crisis and environment pollution the clean energies are required. Biomass is a commercially renewable energy resource that is used for replacing the fossil fuel usage and also reducing the environment problem. Gasification is thermo-chemical process with the limit or sub-stoichiometric of air supplying that is used to extract the energy from biomass by converting the solid

biomass into the combustible gaseous fuel known as ‘Synthesis gas or Syn gas’. In this study we particularly focused on a downdraft biomass gasifier following the advantages of this type are: 1) cheaper than other gasification method, 2) low tar content syn gas and 3) low particulates [1].

Many researchers [2-8] developed the thermo-chemical equilibrium gasification model to describe gasification process by considering the gasifier as single zone or global. To improve the equilibrium model Huang et al. [4] and Jarunghammachote et al. [5] multiplied the constant to the equilibrium constants for fixing the amount of CH_4 and CO to close the experimental results. For the model developing the gasification model has developed by dividing the model into subzones about drying, pyrolysis, oxidation, and reduction zones for improving the performance of the gasification model. For the drying zone, Sharma [9] proposed the diffusion drying model with the preheating condition so, the temperature was constant along the bed length. Bryden et al. [10-11] presented drying and pyrolysis models by using Arrhenius’s expressions. There are temperature conditions for drying model that are drying reaction started when temperature is higher than 95°C while recondensation started if temperature dropped lower than 95°C . For the pyrolysis zone, Babu et al. [12] developed the kinetic pyrolysis model based on Koufopoulos’ mechanism [13] which heating rate, a function of time, does not come from corresponding inlet heat. Ratnadhariya et al. [14] presented the equilibrium model of pyrolysis to find the composition of pyrolysis gas. For the oxidation zone, Sharma [9] proposed the sequence equilibrium model of oxidation zone by considering the value of reaction rate of this zone. For the reduction zone, Giltrap et al. [1] have studied a steady state kinetic model with the plentiful char condition and incorporated several factors such as particle size and number of active carbon site into their pre-multiplier that are called ‘Char Reactivity Factor’ (CRF) which represents the relative reactivity of different char types [1]. Roy et al. [15-16] and Sharma [17] developed the finite kinetic model of reduction zone related the height, angle and diameter of gasifier which can be used for gasifier design.

Therefore in this study we will develop the mathematical model of four zones of downdraft gasification process in order to predict the final gas compositions, and the temperature of each zones. In the parametric study we will focus on the effects of the moisture content, and the equivalence ratio on the height of drying, pyrolysis, and reduction zones which can be used to study and evaluate for the gasifier design.

2. Methodology

In this study the downdraft biomass gasification model was developed and divided into four modules by considering the four main processes of the gasification are drying, pyrolysis, oxidation, and reduction. The biomass feedstock is fed into the top of gasifier as the drying module and the air is injected into the oxidation module to provide the heat for using in the endothermic reactions of other modules as shown in Fig. 1. The results of drying module come in to the pyrolysis module as the reactants which the pyrolysis results are the reactants of the oxidation module as well. The products of oxidation as the reduction reactants react following the reduction reactions to produce syn gas that comprise H_2 , CO , CO_2 , H_2O , CH_4 , N_2 , and remaining char. The assumptions of this study are listed below:

- 1) All Gases are ideal
- 2) All processes operate under steady state condition
- 3) For equilibrium oxidation module residence time is enough to reach the thermo-chemical equilibrium.
- 4) Pressure is constant at atmospheric pressure.

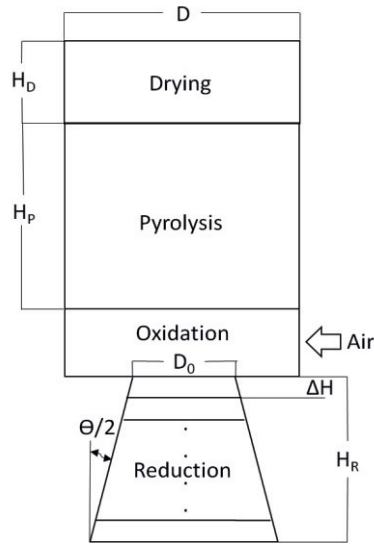


Fig. 1. A schematic diagram of the downdraft biomass gasification of this study

2.1. Drying module

The moisture content of biomass feedstock vaporized in this module by heat supplying from the oxidation module. The model of drying module was adopted from the finite rate kinetic model of Roy et al. [15] for applying the drying process. The temperature of drying module rises from initial temperature ($T_0 = 298$ K) until temperature reach 368 K and then the vaporization of moisture content starts. After the moisture content completely vaporized the drying temperature still increases until at 473 K the pyrolysis process will replaces which can be determined the optimum height of the drying zone. The rate of drying reaction (r_d), mol/(m³·s), as a function of drying temperature (T_d) is as follows [10-11, 18]:

$$r_d = k_d C_{H_2O,L} \quad (1)$$

$$k_d = A_d \exp\left(\frac{-E_d}{R_u T_d}\right) \quad (2)$$

where k_d is the kinetics constant of the drying process in s⁻¹, $C_{H_2O,L}$ is the concentration of moisture content in mol/m³, A_d is the pre-exponential factor = 5.13×10^6 s⁻¹ [19], E_d is the activation energy of drying reaction = 88 kJ/mol [10-11], and R_u is the gas universal constant = 8.314 J/(mol·K) The drying temperature as a function of height (H_D) can be obtained from the energy balance between input and output of each control volume.

2.2. Pyrolysis module

The dry biomass feedstock thermally decomposes to volatile gases, and char without air/oxygen. Koufopoulos et al. [13] developed the two steps reaction mechanism kinetic model which biomass decomposes to volatile gases, and char in the first step and the products of first step further react with each other to produce volatile gases, and char in the second step. The optimum point of the model is at the concentration of biomass of 0.03 because beyond this point the pyrolysis is very slow and there is little importance [12]. In this study the Koufopoulos' mechanism was used by the pyrolysis process replaced the

drying process when the temperature reaches 473 K. The heating rate can be obtained from the transferring heat of the oxidation module by using iterative calculation until the heating rate converged and also corresponded to other modules. To find the compositions of volatile gas (in mol) the equilibrium model was need to apply in this module. The four balancing equations of C, H, O, and N were modeled with the two equilibrium constant equations of the Water gas shift ($\text{CO} + \text{H}_2\text{O} = \text{CO}_2 + \text{H}_2$), and Methanation ($\text{C} + 2\text{H}_2 = \text{CH}_4$) reactions [14] by using the pyrolysis temperature and the amount of char from kinetic model. There are six unknowns (amounts of H_2 , CO , CO_2 , H_2O , CH_4 and N_2) and six equations so the composition of volatile gases can be computed. To determine the height of the pyrolysis zone the area of this zone is assumed to be constant as the cylindrical shape. The pyrolysis time can be obtained from the results of this module and is multiplied by the superficial gas velocity. We can then find the height of pyrolysis zone (H_p). The superficial gas velocity (V_g) can be expressed as [20]:

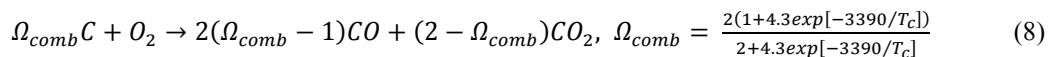
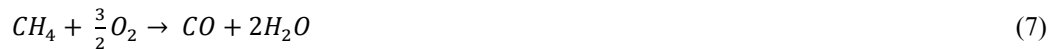
$$V_g = \frac{R_u \cdot T_p}{P \cdot \varepsilon_b} \sum_{i=1}^6 N_{g,i} \quad (3)$$

$$N_{g,i} = \frac{4 \cdot x_{g,i} \cdot \dot{m}_{fuel}}{\pi \cdot D^2} \quad (4)$$

where T_p is the pyrolysis temperature in K, P is the atmospheric pressure in Pa, ε_b is the void fraction = 0.5 [21], $x_{g,i}$ is the gas composition in mol ($i = 1$ to 6 represent H_2 , CO , CO_2 , H_2O , CH_4 and N_2 respectively), \dot{m}_{fuel} is the feed rate of biomass feed stock in g/s, and D is the diameter of the pyrolysis zone.

2.3. Oxidation module

The air is injected to this zone to react with the products of pyrolysis module to provide heat for using in the endothermic reactions. In this study the sequence equilibrium model was applied by considering the reaction rates of these reactions as follows [21-22]:



where T_c is the temperature of oxidation zone. The rates of reaction as a function of temperature of (5) to (8) are the indicator to consider the sequence of the oxygen reacting. We found that the reaction rates of (5) is the highest and (6), (7), and (8) are minor respectively. So it means that oxygen firstly reacts with H_2 . The remaining oxygen after reacted with H_2 continuously reacts with CO , and CH_4 respectively and then finally reacts with C to produce oxidation products. In the equilibrium calculation the water gas shift reaction was considered to use in this model because this reaction can be safely applied for the fuel rich oxidation condition [9, 17, 23] The balance of energy equation was used for computing the equilibrium temperature of oxidation module and this equation was also integrated supplying heat that transfers to drying module and pyrolysis module to find the corresponding heating rate. N_2 from air does not participate in any reactions, it only comes with the syn gas as diluter [1].

2.4. Reduction module

In this module there are four reduction reactions are Boudouard (R1: $C + CO_2 = 2CO$), Water gas primary (R2: $C + H_2O = CO + H_2$), Methanation (R3: $C + 2H_2 = CH_4$), and Steam reforming (R4: $CH_4 + H_2O = CO + 3H_2$) reactions which the Water gas shift reaction is negligible because it was found that had a little effect on final results by Giltrap et al. [1]. The reaction rates equations of reaction that noted above are expressed as the Arrhenius equations, which the values of activation energy (E_R) and pre-exponential factor (A_R) can be obtained from Wang et al. [24], are shown as:

$$r_{R1} = C_{RF} \cdot A_{R1} \exp\left(\frac{-E_{R1}}{R_u T_r}\right) \left(y_{CO_2} - \frac{y_{CO}^2}{K_{R1}}\right) \quad (9)$$

$$r_{R2} = C_{RF} \cdot A_{R2} \exp\left(\frac{-E_{R2}}{R_u T_r}\right) \left(y_{H_2O} - \frac{y_{CO} y_{H_2}}{K_{R2}}\right) \quad (10)$$

$$r_{R3} = C_{RF} \cdot A_{R3} \exp\left(\frac{-E_{R3}}{R_u T_r}\right) \left(y_{H_2}^2 - \frac{y_{CH_4}}{K_{R3}}\right) \quad (11)$$

$$r_{R4} = C_{RF} \cdot A_{R4} \exp\left(\frac{-E_{R4}}{R_u T_r}\right) \left(y_{CH_4} y_{H_2O} - \frac{y_{H_2}^3 y_{CO}}{K_{R4}}\right) \quad (12)$$

where C_{RF} is the char reactivity factor, T_r is the temperature of the reduction module, y_i is the mol fraction of gas species i , K_{R1-R4} are the equilibrium constant of reduction reaction of 1 to 4 which can be determined from the standard Gibbs function of formation [5]. Roy et al. [15] found that the suitable value of C_{RF} should be equal to 100 when compared to experimental data. The finite rate kinetic model of Roy et al. [15-16] was used in this study. The energy balance equation was used to calculate the reduction temperature of each control volumes. We integrated the heat transfer between the control volumes into the model but it does not have significant effect on the results. In this module the critical height of the reduction zone (H_R), the minimum height that char is completely consumed of this zone, was determined.

3. Results and Discussions

In this part the gasification model was validated with the experimental data of Jayah et al. [25] on the mol fraction (%dry basis) by using the data of biomass feedstock and the dimension of the gasifier as shown in Table 1.

Table 1. The data of the biomass feedstock (Rubber wood) and dimension of gasifier [25]

Parameter	Ultimate analysis (%)
C	50.6
H	6.5
O	42.0
N	0.2
Ash	0.7
Parameter	(m)
D	0.92
D ₀	0.10
H _R	0.22
θ	61°

Table 2. shows the comparison of the model prediction against the experimental data of Jayah et al. [25] on gas composition (%dry basis) with conditions of MC = 16% and A/F = 2.2, and MC = 14.7% and A/F = 2.37. The amount of H_2 and CO_2 are slightly over-prediction while CO and N_2 are slightly under-prediction when compared to the experimental data. The amount of CH_4 is also lower than the

experimental data of both conditions. From the comparison the four modules downdraft biomass gasification model shows a good agreement with the experimental data.

Table 2. The comparison between model prediction and experimental data [25] on gas composition (%dry basis) with conditions of $mc = 16\%$ and $A/f = 2.2$, and $mc = 14.7\%$ and $A/f = 2.37$

Gas composition	MC = 16%, A/F = 2.2		MC = 14.7%, A/F = 2.37	
	Model	Exp.	Model	Exp.
H ₂	18.6	18.3	17.8	17.2
CO	19.0	20.2	19.2	19.4
CO ₂	11.3	9.7	11.0	9.7
CH ₄	0.6	1.1	0.3	1.1
N ₂	50.5	50.7	51.7	52.6

To study the effect of moisture content on the height of each zones the air to fuel ratio is fixed at 2.2 and the moisture content is varied from 0 to 40 %. The increasing of moisture content affects temperature dropping of all zones as shown in Fig. 2a because the moisture content increasing required more heat to vaporize the moisture content to water vapor which directly affects the temperature of all processes.

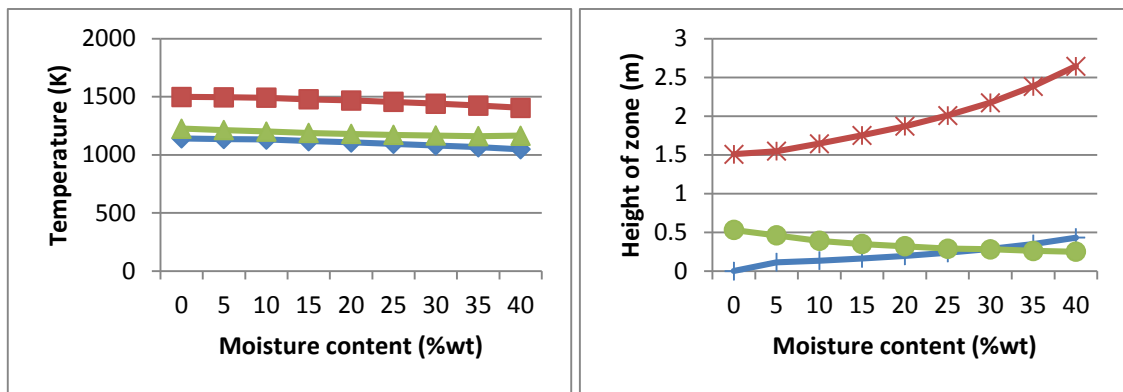


Fig. 2. (a) The final temperature of pyrolysis, oxidation, and reduction zones with the varying of moisture content from 0 to 40 % at $A/F = 2.2$, (T_p : ◆; T_c : ■; T_r : ▲); (b) The height of drying, pyrolysis, and reduction zones with the varying of moisture content from 0 to 40 % at $A/F = 2.2$, (H_D : +; H_P : *; H_R : ●).

Fig. 2b shows the effect of moisture content on the height of drying, pyrolysis, and reduction zones. The height of drying and pyrolysis zones increase with the increasing of moisture content because the temperature of all zones drop so heat is less transferred to drying and pyrolysis zones and drying and pyrolysis processes then spend more long residence time. The critical height of the reduction zone decreases from 0.53 m to 0.25 m with the increasing of moisture content. Because of the moisture content more comes in to the gasifier as the reactant of the reduction zone therefore, the Water gas primary and Methanation reactions more occurred and then more consumed carbon with the decreasing of reduction temperature. For the study of effect of the air to fuel ratio (A/F) the moisture content of feedstock was forced to be 16 % and A/F is varied from 1.8 to 3 in order to study the effect on the height of each zones. The injecting air to the gasifier is more with the increasing of A/F which the oxidation reactions in the oxidation zone also more occur. The temperature of the oxidation rises along the A/F increasing and heat of oxidation reactions more transfers to the other zones to use in the endothermic reactions. So the temperature of all zones also rises as shown in Fig. 3a. Fig. 3b shows the effect of A/F on the height of drying and pyrolysis zones which slightly decrease with the A/F varying because heat more transferred from oxidation zone to drying and pyrolysis zones. So, the drying and pyrolysis processes are more reactivity.

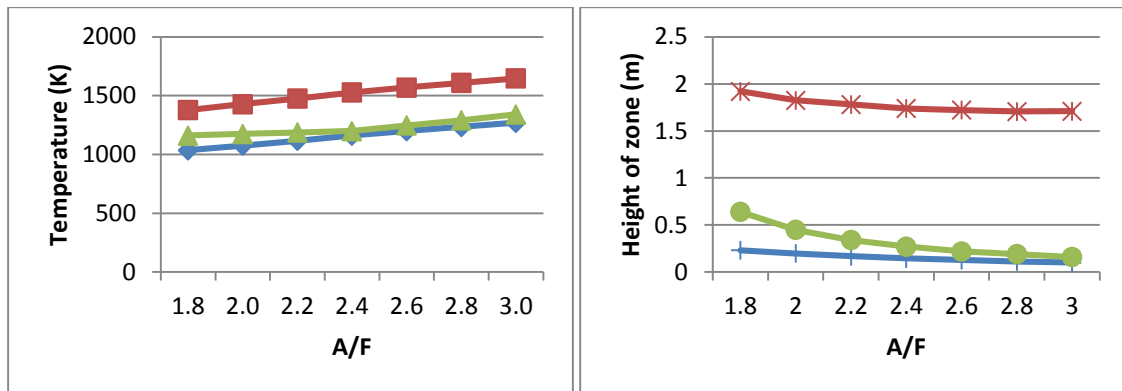


Fig. 3. (a) The final temperature of pyrolysis, oxidation, and reduction zones with the varying of air to fuel ratio from 1.8 to 3 at MC = 16%, (T_p : \blacklozenge ; T_c : \blacksquare ; T_r : \blacktriangle); (b) The height of drying, pyrolysis, and reduction zones with the varying of air to fuel ratio from 1.8 to 3 at MC = 16%, (H_D : +; H_P : \ast ; H_R : \bullet).

The critical height of reduction zone slightly decreased from 0.64 m to 0.16 m with the varying of A/F from 1.8 to 3. Because of the temperature of reduction zone increased which directly resulted the endothermic reduction reactions. Char is more consumed from the reduction reactions more occurring. For another reason the products of oxidation reactions is more and come into the reduction zone as reactants which resulted more reduction reaction occurring. From this parametric study we found that there are many effects of the moisture content and the air to fuel ratio on the height of each zones of the gasifier. The results of this study can be used as the preliminary evaluation in the gasifier design to get the suitable conditions of downdraft biomass gasification process.

4. Conclusion

In this study the downdraft biomass gasification process model was studied and developed by considering to be four modules are drying, pyrolysis, oxidation, and reduction. The finite rate model of drying module started water vaporization when temperature reached 368 K. After the moisture content completely changed to water vapor and temperature reach 473 K the pyrolysis process replaced with the corresponding heating rate that came from heat transferring from oxidation process. The sequence model was applied to the oxidation module by considering the sequence of the reaction rate of four oxidation reactions. Oxygen reacted following the sequence of rate of oxidation reactions. For the reduction module the finite rate kinetic model was used by following four reduction reactions to find the composition of synthesis gas that comprises H_2 , CO, CO_2 , H_2O , CH_4 and N_2 . The validation between model prediction and experimental data showed a good agreement. In the parametric study we focused on the effects of moisture content and air to fuel ratio on the height of drying, and pyrolysis zone and also critical height of reduction zone, minimum height that char is completely consumed in reduction reactions. For the studying of effect of moisture content air to fuel ratio was forced to 2.2 and moisture content was varied from 0 to 40 %. Similarly, to study the effect of air to fuel ratio the moisture content was fixed at 16 % and air to fuel ratio was varied from 1.8 to 3 as well. The height of drying, and pyrolysis zones increased with the moisture content increasing while the critical of reduction zone decreased. For the effect of air to fuel ratio the height of drying, and pyrolysis zones including critical height of reduction zone decreased along the air to fuel ratio increasing. The results of this study can be used for the downdraft gasifier design to choose the reactor dimension corresponded to the actual operation with actual conditions.

Acknowledgements

The authors would like to thank JGSEE (The Joint Graduate School of Energy and Environment) and Department of Mechanical Engineering at KMUTNB (King Mongkut's University of Technology North Bangkok) for financial and technical supports.

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